REMARKS/ARGUMENT

Regarding the Claims in General:

Claims 19-54 are now pending. Claim 18 has been replaced by claim 40, and claims 20-21, 26, 28, 31-35, and 37-39 have been amended to clarify certain recitations in the claims as previously presented, to eliminate some possible ambiguities, and to further improve the form of the claims for purposes of examination under U.S. practice. The claims have not been narrowed by these changes.

Claims 41-54 have been added to provide applicants with additional protection to which they appear to be entitled in light of the prior art.

Regarding The Allowable Subject Matter

Applicants note with appreciation the indication that claims 19, 21-26, and 31-35 would be allowed if rewritten in independent form incorporating the limitations of their respective parent claims. Because these claims are all ultimately dependent on claim 40, which is believed to be allowable as explained below, they have been retained in dependent form pending the Examiner's further consideration.

Regarding the Prior Art Rejections:

In the outstanding Office Action, claims 18, 20, 27, 28, 30, and 36 were rejected under 35 U.S.C. 103 as being unpatentable over Kauffman U.S. Patent 5,368,670 (Kauffman) in view of Gibbs et al. U.S. Patent 5,447,179 (Gibbs), Ziu U.S. Patent 4,786,088 (Ziu) and Pool et al. U.S. Patent 6,402,201 (Pool). Claim 29 was rejected as being unpatentable over Kauffman, Gibbs, Ziu, and Pool further in view of Stevens U.S. Patent No. 5, 474,721 (Stevens). Applicants respectfully request reconsideration and withdrawal of these rejections.

Preliminarily, the Examiner is respectfully reminded that to support a rejection under 35 U.S.C. 103, there must be objective evidence in the record and an explanation of the reasons one of ordinary skill in art would have been motivated to select and combine the references, *In re Lee,* 277 F.3d 1338,1343, 61 U.S.P.Q.2d 1430, 1433-4 (Fed. Cir. 2002); *In re Fritch,* 972 F.2d 1260, 1265, 23 U.S.P.Q.2d 1780, 1783 (Fed. Cir. 1992). ([The Examiner] can satisfy this burden only by showing some objective teaching in the prior art or that knowledge generally available to one of

ordinary skill in the art would lead that individual to combine the relevant teachings of the references". See also: *In re Fine,* 837 F.2d 1071, 1074, 5 U.S.P.Q.2d 1596, 1598 (Fed. Cir. 1988).

Applicants' own teachings, however, are not prior art, and can not be used to provide such motivation, *In re Fine,* 837 F.2d at 1075, 5 U.S.P.Q.2d at 1600 ("To imbue one of ordinary skill in the art with knowledge of the invention in suit, when no prior art reference or references of record convey or suggest that knowledge, is to fall victim to the insidious effect of a hindsight syndrome wherein that which only the inventor taught is used against its teacher".)

The Examiner must therefore find in the prior art itself objective evidence of a teaching, suggestion or motivation for one skilled in the art to combine the references. It is respectfully submitted that she has not, and indeed, can not do so in this instance.

In considering the question of motivation for combining the applied references, the Examiner is respectfully reminded that references from non-analogous arts are not legitimately combinable. It has long been understood that:

> In resolving the question of obviousness under 35 USC 103 . . . full knowledge by the inventor [is presumed] of all the prior art in the field of his endeavor. However, with regard to prior art outside the field of his endeavor, we only presume knowledge from those arts reasonably pertinent to the particular problem with which the inventor was involved. (Citations omitted.) The rationale behind this rule precluding rejections based on combination of teachings of references from non-analogous arts is the realization that an inventor could not possibly be aware of every teaching in every art. Thus, we attempt to more closely approximate the reality of the circumstances surrounding the making of an invention by only presuming knowledge by the inventor of prior art in the field of his endeavor and in analogous arts.

In re Wood et al., 599 F.2d 1032, 1036, 202 USPQ 171, 174 (CCPA 1979).

Background of the Invention:

With the foregoing in mind, it is noted that the present invention is directed to double wall pipes used for *offshore,* i.e., deep water, applications, in which the outer pipe is subjected to substantial hydrostatic pressure. Such double walled or pipe-in- pipe (PIP) structures are constructed with an annular space between the pipes which is filled with insulation to keep the oil within the inner pipe at a sufficient temperature to prevent hydrate or wax formation. A benefit of the double walled pipe is that "dry" insulation (a very efficient insulator) can be employed.

To ensure that the insulation is kept dry, damage to the outer pipe must be prevented. This can be extremely difficult to do, however, because the PIP is generally installed on the seabed, and the outer wall can be damaged by ships' anchors, fisherman, by objects falling from ships or by semisubmersible platforms. So it is practically impossible to guarantee that the outer pipe will not be damaged. The art has therefore been willing to accept local damage as long as steps are taken to prevent local damage from spreading to the entire length of pipe.

One solution is to employ water stops, i.e. nylon pieces which seal the annulus of the PIP placed at regular intervals. This conventional practice is adequate for its purpose. However, if the damage on the outer pipe is not a "leak" but a buckle (with no flooding of the annulus), and if the hydrostatic pressure is great enough compared to the pressure in the annulus (which is at atmospheric pressure), a buckle will tend to propagate to the left and right along the entire length of the pipe. This problem does not exist for onshore (or shallow water) installations as the pressure differential between the external pressure and the annulus pressure is not significant enough to allow a buckle to propagate axially when a buckle occurs into outer pipe.

If a buckle does propagate, the insulation filling the annulus can be severely damaged and more probably, the outer pipe will experience multiple points of leakage. Either way, the PIP will become inefficient. This invention addresses the problem of propagation of a buckle along the length of an external pipe of a double-walled offshore pipe due to hydrostatic external pressure.

Conventionally, this problem is addressed by strengthening collars welded at regular intervals along the outside of the outer pipe. Devices of this kind are described in *Buckle Arrestors for Deepwater Pipelines* by Carl G. Langer, presented at the Offshore Technology Conference in Houston, Texas, May 3-6, 1999. A copy of this document was furnished with the communication dated May 19, 2004, and another copy is attached hereto for the Examiner's convenience.

As previously stated, applicants do not consider this document as material to patentability, even though it is probably still the most pertinent, i.e., analogous, prior art of record.

Using this conventional technology, if a buckle occurs, it will propagate only between two adjacent external collars. However, this technique is suitable only when using the J-Lay technique, as described in the specification, because an external device on the outer pipe does not impede the J-Lay operation. However, when the "reeling" or reel lay technique is employed, external collars are not suitable. The external devices prevent the pipe from being stored on the vessel reel, so the collars must be installed and welded in place during the laying operation offshore. This requires that

the unreeling process be stopped each time a collar is to be installed, and negates the benefits of reel laying.

The Nature of the Invention

According to the invention, the buckle propagation problem is addressed in a way which does not impede use of the reel lay technique because it requires no stopping, or only very short stops during the unreeling - straightening process. Specifically, applicants' technique is to install pairs of sealing blocks at regular, relatively short intervals in the annular space between the inner and outer pipes, e.g., every 100 m. The spacing between the two seals of each pair is on the order of the outer diameter of the outer pipe, again, by way of example, 1m.

Between the two sealing blocks, there is injected a curable compound that solidifies to provide mechanical strength to support the outer pipe and to stop the propagation of a buckle. Thus, if the buckle arresters are spaced every 100m, a buckle will propagate only within the 100m spacing between the adjacent buckle arrestors, and the rest of the pipe will be safe.

The length of the "solid" annular "injected buckle arrestor" depends on the water depth (hydrostatic pressure), the thickness and resistance of the outer pipe etc. The interval between adjacent buckle arresters depends on the insulation capability required for the pipe in relation to the temperature of material carried by the pipeline, the chemical composition of the transported material, the total length of the pipe, etc.

The Applied Prior Art:

Although two of the applied references (Kauffman and Ziu) disclose double walled structures including a carrier pipe within a radially spaced containment pipe, only Ziu even mentions concerns about buckling (see col. 9, lines 34-62). Even here, the concern relates to buckling *of the inner carrier pipe,* and not the outer containment pipe, arising out of temperature differentials, and not great hydrostatic pressure. Ziu mentions numerous applications for thermoplastic double walled pipe (see col. 1, line 36-col. 2, line 35, but significantly, none of these relate to offshore pipelines.

Moreover, in Ziu, the concern is not about axial propagation of buckling, but about contact between the inner and outer pipes (Ziu does not use thermal insulation between the inner and outer pipes in any event), or forces set up between the support arms 22 and the containment pipe in areas of maximum buckling (col. 9, lines 40-46).

Finally, Ziu's solution to his problem is to employ a solid restraint coupling 80 as the means of attaching adjacent pipe sections, as compared to the spaced pairs of seals with a curable compound injected between them as in the present invention. An external clamping ring 88 is then placed over the restraint coupling which applies radially inward force to prevent relative movement between the inner an outer pipes (col. 9, lines 51-59). This typical prior art is completely different from that employed by applicants, and is unsuitable for use with reeled pipe, as noted above. Not surprisingly, there is no mention in Ziu of reenable pipe applications.

Kauffman relates to a double walled tank or pipe, for which, like Ziu, the objective is to prevent leakage of the inner wall due to buckling (see Figs. 4 and 5). There is no suggestion or teaching as to how to deal with a situation in which local buckling can not, as a practical matter, be prevented.

Kauffman prevents buckling by creating an entirely rigid structure using closely spaced ribs which also serve as spacers between the inner and outer pipes. There are no buckle arrestors at widely spaced intervals between spacers. Kauffman's pipe might function successfully in an off shore, deep water environment, but the rigidity prevents use of the reeling technique for laying the pipe in offshore applications, because the structure can not be plastically deformed to be wound on a vessel reel and then straightened while being laid offshore. Further, as in the case of Ziu, the strengthening elements of Kauffman are quite different from the spaced pairs of seals with a curable compound injected between them, as in the present invention.

In short, even the two closest references are unrelated to applicants' field of endeavor, i.e., deep offshore pipelines which can be laid from reels. They are also unrelated to applicants' specific problem, i.e., preventing propagation of unavoidable buckles due to high hydrostatic pressure. They are even unrelated to applicants' solution to the problem i.e., use of spaced pairs of seals with a curable compound injected between them.

Even more remote in terms of field of endeavor and problem to be solved are the remaining references. Pool, for example, relates to single wall pipe with "wet" insulation. The goal of this patent is to protect the corrosion coating at the pipe welds. In this pipe, propagation of a buckle is not an issue because of the internal pressure of the oil. This has nothing to do with the problem of preventing buckle propagation in the outer pipe of a PIP because of the great hydrostatic pressure on the outer pipe compared to atmospheric pressure in the annulus between the pipes, and the fact that the thermal insulation in the annulus is not sufficiently strong to prevent buckling of the outer

pipe. Pool only teaches injecting foam under a sleeve on a single pipe at the joint between pipe sections. It isn't concerned with reelable pipe or even double walled pipe.

The Stevens and Gibbs patents are even more remote as to both field of endeavor and problem being solved. Gibbs teaches how to make a double walled tube suitable for use as a brake line in which the inner tube and the outer tube are separated by an intermediate bonding layer which fuses the inner and outer tubes together.

Stevens relates to forming composite structures. It teaches a practitioner in the offshore pipeline art nothing about preventing buckle propagation in deep offshore pipe lines by locally strengthening the outer pipe at selected intervals in a way that permits the pipe to be laid using the reel lay technique.

Accordingly, as a matter of law, the references are not legitimately combinable, both because there is no motivation in the prior art for the combination, and also as a matter of law because the references are from non-analogous arts. Even if the references are combined as proposed by the Examiner, the result does not meet the terms of the present claims.

Base method claim 40, for example, is directed to a method of manufacturing a reelable double-walled rigid pipe for underwater transportation of fluid. The pipe is described as comprising an inner flow pipe, the interior of which defines a passage for transporting the fluid, an outer carrier pipe which surrounds the flow pipe, and a plurality of longitudinally spaced separating elements between the inner and outer pipes which define an annular space therebetween, which is capable of arresting longitudinal propagation of buckling of the outer carrier pipe.

Neither Kauffman nor Ziu, whether considered singly or in combination, discloses, teaches or suggests a method for manufacturing a reelable deep water double walled pipeline which resists propagation of buckles in the outer pipe. Both are designed to *prevent* buckling, but at the expense of making the pipe reelable.

Gibbs is the only reference which discloses a double walled tube which can be coiled, but as noted above, Gibbs' tube is for us as a brake line - - a completely non-analogous art - - and could not be used as a deep water pipe line, or anything even remotely similar. Gibbs does not teach anything which could be applied to make Kauffman, or, for that matter, with Ziu, into a reelable pipe. Nor is there anything in Stevens or Pool which remedies this fatal deficiency in the proposed combination of Kauffman, Ziu, and Gibbs.

The specific method steps claimed include:

> selecting dimensions and properties of the inner pipe and the carrier pipe according to an intended fluid transportation application, and an intended pipeline location, and to have suitable mechanical properties which permit the double walled pipe to be plastically deformed for reeling on a vessel reel and then straightened while being laid offshore. . .

There is nothing in any of the applied references which suggests selecting dimensions and properties of the inner pipe and the carrier pipe to have suitable mechanical properties which permit the double walled pipe to be plastically deformed for reeling on a vessel reel and then straightened while being laid offshore.

Claim 40 further recites:

> assembling a double walled pipe using the selected carrier and flow pipes, and the separating elements, and also including at least one pair of sealing blocks axially spaced apart between the outer wall of the flow pipe and the inner wall of the carrier pipe. . .

Only Ziu discloses anything which could reasonably correspond to the claimed separating elements and also another structure concerned with buckling, i.e., support clips 18 and restraint couplings 80. To substitute these for some of Kauffman's ribs, would serve no purpose in Kauffman, and in any case, the only possible motivation for such a substitution would be applicants' own teachings.

Moreover, even if such a substitution were made, the result would not be at least one pair of axially spaced sealing blocks:

> . . . having radially opposite faces [spaced] so that the axial length of the annular region is at least equal to 0.5 times the external diameter of the carrier pipe;

Neither Kauffman, in the context of ribs 16, nor Ziu, in the context of restraint couplings 80, teach or suggest any relationship between axial length and the outside diameter of the outer pipe. The portion of Kauffman cited by the Examiner does not even refer to the outside diameter of the outer pipe.

Finally, none of the references teaches of suggests filling an annular region between axially spaced sealing blocks with a curable compound, which is then cured in place. Obviously, applicants do not claim to have invented use of curable compounds within annular spaces, but the prior art does not teach or suggest such use in a buckle arrestor for a reelable deep water pipeline.

All other previously rejected claims are directly or indirectly dependent on claim 40, and are therefore patentable for the reasons stated above. Claims 42-54 are apparatus claims patterned after claims 19-41, and are also patentable for the same reasons.

In view of the foregoing, favorable reconsideration and allowance of this application are respectfully solicited.

EXPRESS MAIL CERTIFICATE

I hereby certify that this correspondence is being deposited with the United States Postal Service as Express Mail Post Office to Addressee (mail label: EV 343681539 US: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450 on the date indicated below:

Dorothy Jenkins
Name of applicant, assignee or Registered Representative

Dorothy Jenkins
Signature

November 15, 2004
Date of Signature

LAH:cbf/lac

Respectfully submitted,

Lawrence A Hoffman

Lawrence A Hoffman
Registration No.: 22,436
OSTROLENK, FABER, GERB & SOFFEN, LLP
1180 Avenue of the Americas
New York, New York 10036-8403
Telephone: (212) 382-0700

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OTC 10711

Buckle Arrestors for Deepwater Pipelines

Carl G. Langner / Langner & Associates

This paper was prepared for presentation at the 1999 Offshore Technology Conference held in Houston, Texas, 3–6 May 1999.

Abstract

Progress has been made in the design of buckle arrestors, or more precisely collapse arrestors, for deepwater pipelines. Empirical relationships have been developed for the design of both integral ring and grouted sleeve arrestors, forming the basis of a simple and straightforward design procedure. The good agreement between the latest design formulas and the crossover pressure data obtained from large scale tests by Shell E&P Technology Company and by Professor Kyriakides at U.T. Austin over the past few years, should result in more efficient and reliable buckle arrestors for deepwater pipelines.

Introduction

An offshore pipeline which has been damaged locally may fail progressively over long distances by a propagating collapse failure driven by the hydrostatic pressure of the seawater. The pressure required to propel a propagating collapse is much smaller than the pressure required to initiate collapse of an undamaged pipe. For deepwater pipelines it is often uneconomical to design the pipeline with sufficient strength to prevent a propagating collapse failure. Such pipelines are designed to prevent buckling and collapse failures due to normal combined bending and external pressure loads, but are left vulnerable to propagating collapse failures initiated under extraordinary circumstances.

In such cases, it is feasible to install buckle arrestors, such as thick-wall rings, at intervals along the pipeline. A series of such arrestors, each sufficiently strong to stop a propagating collapse failure, will limit the extent of damaged pipe in event of a mishap. In general, the distance between buckle arrestors is selected to enable repair of the flattened section of pipeline between two adjacent arrestors, at "reasonable" cost. For pipelines installed by J-Lay, the buckle arrestors also serve as pipe support collars. In this case the distance between arrestors is simply the length of each J-Lay joint.

Three types of buckle arrestors are in common use, namely Grouted Sleeve arrestors, Integral Ring arrestors, and Thick Wall Pipe Joints. Grouted Sleeve arrestors are steel sleeves that are slid over the ends of selected pipe joints and are grouted in place, as shown in Figure 1, before being installed offshore. Grouted Sleeve arrestors are preferred, where feasible, because of their low cost. However, this type of arrestor has limited usefulness in deep water because, as external pressure increases, a collapsed pipe will transform from its normal flat "dogbone" cross section into a C-shaped cross section which then passes through the arrestor. Hence, for sufficiently deep water, even an infinitely rigid Grouted Sleeve arrestor is ineffective.

Integral Ring arrestors are thick-wall rings that are welded into selected pipe joints, as illustrated in Figure 2, before being installed offshore. Integral Ring arrestors are used for pipelines in which the strength of sleeve type arrestors is not adequate, and for J-Lay applications that require a support collar on each pipe joint. These arrestors are very efficient in terms of strength for a given amount of steel, but are more expensive than sleeve arrestors because of the additional welding required. Thick Wall Pipe Joint arrestors are special pipe sections, each designed to prevent collapse propagation, that are welded into a pipeline at intervals. A Thick Wall Pipe Joint is essentially a very long integral ring arrestor, but is much less efficient in the amount of steel used.

Early studies of propagating buckles and buckle arrestors, Refs. 1 through 3, provided general guidance for the design and utilization of buckle arrestors on offshore pipelines. The many subsequent publications by Kyriakides and his colleagues, Refs. 4 through 14, expanded and refined our understanding of the various phenomena involved in initiation, propagation, and arrest of collapse failures in pipelines and other structures. This paper presents new design formulas for "narrow" integral ring arrestors which correlate well with the existing data. Such arrestors are particularly useful for deep-water pipelines because of their high strength buckle arresting capabilities. Also presented are alternative design relationships for "wide" integral arrestors and for

grouted sleeve arrestors, which have comparable accuracy to other existing formu-lations, such as Refs. 4 and 14.

Because of the complexity of the buckle crossover phenomenon, buckle arrestor design relationships are empirical. Two distinct sets of test data exist for design of Integral Ring arrestors: one set obtained from five full-scale tests of 12" and 18" pipes/arrestors conducted in 1989, 1994, and 1996; and the other set obtained from 35 tests of 4.5" OD pipes/arrestors conducted in 1982 and 1996. These data are listed in Tables 1 through 3. The two sets of data differ in the length-to-thickness ratios of the arrestors, being $L/h = 0.9 - 1.8$ for the full-scale tests and $L/h = 4.6 - 21$ for the smaller pipe tests. They also differ in arrestor efficiencies as will be explained in the data comparisons section below. In addition to the data for integral ring arrestors, this paper presents 17 new test data for Grouted Sleeve arrestors obtained from 6" and 16" pipes in 1996. These data are listed in Table 4.

Arrestor Design Formulas

The following pipe properties must be computed for each pipeline section before performing buckle arrestor design calculations.

Collapse pressure

$$P_c = P_y P_e/(P_y^2 + P_e^2)^{1/2} \quad \text{(1)}$$

$$P_y = 2Y\, t/D \quad \text{and} \quad P_e = 2.2E(t/D)^3$$

Propagation pressure

$$P_p = 24\, Y\, (t/D)^{2.4} \quad \text{(2)}$$

Minimum crossover pressure

$$P_m = 1.35\, \gamma\, H_{max} \quad \text{(3)}$$

Minimum arrestor depth

$$H_a = P_p/1.25\, \gamma \quad \text{(4)}$$

In these formulas, D is pipe outside diameter, t is pipe wall thickness, Y is yield stress (SMYS), E is elastic modulus, γ is the density of seawater, and H_{max} is the maximum water depth associated with a given section of pipeline. The collapse pressure P_c is a lower bound prediction of the net external pressure required to initiate a collapse failure in a nominally round pipe. The propagation pressure P_p is the minimum external pressure that will cause a collapse failure to propagate along a pipeline. Eqns. (1) and (2) are well established in the literature as appropriate for collapse design of pipelines (Refs. 15, 16); however, other equivalent formulas may be used if preferred.

The strength of any buckle arrestor is expressed by its crossover pressure P_x, which is the minimum external pressure that can force a collapsed section of pipe to "cross over" the arrestor and begin collapsing the undamaged pipe on the other side. The minimum crossover pressure for a "weak" arrestor is simply the propagation pressure P_p and the maximum crossover pressure for a "strong" arrestor is simply the collapse pressure P_c of the pipe. A useful parameter that varies between 0 and 1, depending on the arrestor strength, is the arrestor efficiency η, defined by

$$\eta = (P_x - P_p)/(P_c - P_p) \quad \text{(5)}$$

The design crossover pressure (as calculated below) must equal or exceed the minimum crossover pressure P_m, thus providing a minimum safety factor of 1.35 for any buckle arrestor. Buckle arrestors must be employed along a pipeline at all depths greater than the minimum arrestor depth H_a. At depths less than H_a a pipeline is in no danger of collapse propagation. Note that values of P_c, P_p, P_m, and H_a must be computed for every section of a pipeline that has different pipe specifications.

Thick Wall Pipe Joint. Thick Wall Pipe Joints have been used as buckle arrestors in situations where suitable thick-wall joints are readily available and where the weight of the suspended pipeline during laying is not a critical issue. The design of a thick wall pipe joint arrestor is obtained by equating the minimum crossover pressure P_m (Eqn. 3) with the design crossover pressure P_x which is the same as the propagation pressure P_p (Eqn. 2), and solving for the thickness of the Thick Wall Pipe Joint. Thus

$$t/D = [P_m / 24\, Y]^{0.4167} \quad \text{(6)}$$

Integral Ring Arrestors. Integral Ring arrestors are forged and/or machined weld-neck rings that are butt-welded into a pipe joint that has been cut into two pieces, as shown in Fig. 2. A less expensive version of an integral ring arrestor slides over the pipe and is fillet-welded both sides onto the outside of the pipe joint. Special restrictions may have to be placed on the utilization of this type of arrestor because of stress concentrations, etc. As mentioned previously, integral arrestors are required for applications in which the strength of sleeve-type arrestors is not adequate, and for J-Lay applications that require a support collar on each pipe joint.

Integral Ring arrestors may be categorized as either "narrow" or "wide". Narrow arrestors, in which the length-to-thickness ratio varies between $L/h = 0.5 - 2.0$, are used primarily for pipelines installed by J-Lay; here the arrestor doubles as a collar for supporting the suspended pipe span. Wide integral arrestors, where $L/h > 2$, are used primarily for pipelines installed by S-Lay, because of the easier passage of this type of arrestor through the tensioners and over the stinger rollers. Two different values of the factor k are used in the following design formulation depending on whether the arrestor is narrow or wide. The recommended design formulas for

Integral Ring arrestors are as follows, assuming that the design crossover pressure P_x is everywhere equal to or greater than the minimum crossover pressure P_m (Eqn. 3).

$$\eta \geq \begin{cases} \lambda/k, & 0<\lambda<k \\ 1, & \lambda>k \end{cases} \quad \text{(7)}$$

where
$$k = \begin{cases} 5 & \text{for } 0.5<L/h<2 \text{ (narrow)} \\ 8 & \text{for } L/h>2 \text{ (wide)} \end{cases} \quad \text{(8)}$$

and
$$\lambda = L P_a / D P_p \quad \text{(9)}$$

$$P_a = 24\, Y_a (h/D)^{2.4} \quad \text{(10)}$$

Here η is the arrestor efficiency factor, as defined by Eqn. (5), and λ is the arrestor strength factor, which depends on the arrestor length L, thickness h, yield strength Y_a, and characteristic pressure P_a. The design factor k = 5 is recommended for a narrow arrestor and k = 8 is recommended for a wide arrestor, as indicated. Under the condition that $0 < \lambda < k$, Eqns. (7)-(9) can be solved explicitly for the arrestor length L in terms of given values of h, Y_a, D, etc. Thus

$$\frac{L}{D} \geq \frac{k P_p}{P_a} \left(\frac{P_x - P_p}{P_c - P_p} \right) \quad \text{(11)}$$

For $\lambda \geq k$, the design relationship reduces to $P_x \geq P_c$. Here the arrestor is sufficiently strong that the external pressure must equal or exceed the collapse pressure of the pipeline before a buckle can cross the arrestor.

Grouted Sleeve Arrestor. Grouted Sleeve arrestors are forged or fabricated steel cylinders, typically with dimensions of L/D = 0.5 – 2.0, that are slid over the end of a pipe joint, and grouted in place near the middle of the joint. See Fig. 1. The gap between pipe OD and sleeve ID should be as small as possible to achieve maximum arrestor strength. An annular gap of 1-2 percent of the pipe diameter is recommended. Typical grout materials that have been used are portland cement, sand-filled epoxy, and two-part polyurethane. Sleeve arrestors generally are the lowest cost type of buckle arrestor, but may not be suitable in deep water due to their limited arrestor strength. As mentioned previously, at the crossover limit, the cross section of a buckled pipeline can change from the "dog-bone" shape typical of free buckle propagation, to a "C" shape that enables the collapse wave to pass through a sleeve-type arrestor.

Two types of sleeve arrestors have been used, those that are fairly rigid and remain essentially undeformed, and those that deform significantly during a crossover event. Only the former are considered in this paper, since the current focus is on deepwater pipelines. Design formulations pertaining to deformable sleeve-type arrestors are given in Refs. 3 and 4. The recommended design formulas for Grouted Sleeve arrestors are as follows, assuming that the design crossover pressure P_x is everywhere equal to or greater than the minimum crossover pressure P_m (Eqn. 3). The strength factors

$$\lambda \geq 3, \quad L/D \geq 0.5 \quad \text{(12)}$$

imply
$$P_x \geq \min(P_1, P_2) \quad \text{(13)}$$

where
$$P_1 = 2.4\, P_p, \quad P_2 = P_p + (P_c - P_p)/3 \quad \text{(14)}$$

The restriction on the strength factor ($\lambda \geq 3$) generally can be met by choosing the arrestor thickness to be at least two times the pipe wall thickness ($h/t \geq 2$), although a thinner arrestor is possible if the arrestor length is greater than the pipe diameter. Note that the predicted crossover pressure P_x is the minimum of two different formulas, P_1 and P_2. Both formulas are presented here, as it is not clear from the comparisons with existing data which of these more accurately predicts the crossover pressure of a Grouted Sleeve arrestor. The outside diameter (OD) of the arrestor is given by

$$D_a = D + 2h + g, \quad g = \text{grouted gap} \quad \text{(15)}$$

Comparison with Test Data

Figure 3 compares the Integral Ring arrestor design formula (Eqns. 7,8) with the five full-scale buckle arrestor test data obtained by Shell E&P Technology Company in tests conducted in 1989, 1994, and 1996. The data are listed in Table 1. These 12" and 18" pipe samples all utilized "narrow" arrestors, with L/h = 0.9 – 1.8, and all arrestors were configured to serve as J-Lay support collars. Hence the formula with "narrow" design factor, k = 5, was plotted together with the data in Figure 3. Note that the design curve consists of a linear portion relating the arrestor efficiency η and strength factor λ, followed by a horizontal line η = 1, where the latter represents an infinitely rigid buckle arrestor.

Figure 3 shows that the test data are well correlated with the linear portion of the design curve, having at most about 10 percent deviation. The dashed lines in Figure 3 show the anticipated range of data if additional testing were done, and help to emphasize the narrow spread in these data. Except for pure collapse tests of pipes without buckle arrestors, no data have been obtained to date to correlate with the horizontal portion of the design curve.

Figure 4 compares the Integral Ring arrestor design formula with the entire set of available test data, including the 18 test data obtained by Shell in 1982, the 17 test data obtained by Kyriakides in 1995, and the five full-scale test data referred to above. These data are listed in Tables 1-3. All 35 of the 4.5" OD test samples utilized "wide" arrestors, with L/h = 4.6 – 21. To highlight the differences between these

data sets, design curves for both the "wide" design factor k = 8 and the "narrow" design factor k = 5, are plotted in Figure 4. The k = 8 design curve provides a reasonable lower bound to the entire data set, and therefore is recommended as a conservative design formula for Integral Ring arrestors in general. The k = 5 design curve obviously applies only to "narrow" arrestors and would be unconservative if used to design a "wide" arrestor. A major conclusion from Figure 4 is that "narrow" arrestors are much more efficient in terms of arresting capability than "wide" arrestors, and therefore will be preferred for many deepwater pipeline applications.

Figures 5 and 6 compare the Grouted Sleeve arrestor design formulae P_1 and P_2 with the 1996 test data listed in Table 4. In these tests the 6" and 16" pipe samples were fitted with sleeve arrestors in which L/D varied between 0.45 and 1.06, and h/t varied between 1.32 and 2.55. Figure 5 plots these data as arrestor efficiency η versus the strength factor λ, as before. For the recommended strength range $\lambda \geq 3$ applicable to deep water, the design formula P_2 reduces to $\eta \geq 1/3$, which is seen to be conservative (except for one point) relative to the test data. Note that the arrestor efficiency η for Grouted Sleeve arrestors never exceeds 0.50. This contrasts with Integral Ring arrestors where η can exceed 1.0.

Figure 6 plots the Grouted Sleeve arrestor data as crossover pressure ratio P_x/P_p versus the strength factor λ. For the recommended strength range $\lambda \geq 3$, the design formula P_1 reduces to $P_x/P_p \geq 2.4$, which is seen to be conservative with respect to the test data. Because both the P_1 and P_2 formulae are conservative, the design formulae (Eqns. 12-14) are justified. It is interesting to note that the maximum crossover pressure ratio P_x/P_p for very rigid sleeve arrestors, is just over 3. Another interesting observation, from both Fig. 5 and Fig. 6, is that there is no increase in the crossover pressure for arrestors with strength factors beyond about 5. This suggests that, for economy, a design range of $\lambda = 3 - 5$ may be optimum for Grouted Sleeve arrestors to be used in relatively deep water.

Design Procedure. Following suggestions in Ref. 14, we recommend the following procedure for the design of buckle arrestors for deepwater pipelines. It is assumed that the pipeline design has been determined for one or more sections in which the diameter, wall thickness, and yield strength are specified. For each such pipeline section:

1. Calculate the collapse and propagation pressures of the pipeline, as well as the minimum crossover pressure P_m and the minimum arrestor depth H_a. If the maximum pipeline depth is less than H_a then no buckle arrestors are required. Otherwise arrestors are required over that portion of the line with depths greater than H_a.
2. Select the type of arrestor and a steel grade of the arrestor. Design equations are given for Grouted Sleeve arrestors, narrow Integral Ring arrestors, wide Integral Ring arrestors, and Thick Wall Pipe Joint arrestors.
3. Calculate an arrestor thickness and length such that the design crossover pressure Px is equal or greater than P_m. Under some situations a Grouted Sleeve arrestor will not yield a design. In this case re-design the arrestor as an Integral Ring or Thick Wall Joint arrestor. In some cases a combination of Sleeve arrestors at the shallow end and Integral Ring arrestors at the deep end are feasible.
4. To minimize risk, particularly in critical applications, it is recommended to perform a full-scale test of the proposed pipe and arrestor, utilizing accepted testing procedures.

Conclusions

1. Buckle arrestor designs exist that can protect subsea pipelines against propagating collapse failures. For shallow and moderate depths the low cost Grouted Sleeve arrestors are usually adequate. The more expensive Integral Ring and Thick Wall Joint arrestors are capable of containing pipeline collapse failures in any water depth, provided the external pressure does not exceed the collapse pressure of the pipe.
2. Design formulas together with a design procedure have been developed for each of the various types of buckle arrestors. Comparisons with test data show that these design formulas are both efficient and reliable.
3. The most efficient buckle arrestors are "narrow" Integral Ring arrestors with thickness and length of similar size. Because of its strength, this type of arrestor will be preferred for many deepwater pipeline applications.

Nomenclature

D = outside diameter of the pipeline, in
D_a = outside diameter of a Grouted Sleeve arrestor, in
E = Young's elastic modulus, psi
h = thickness of buckle arrestor, in
H_a = minimum arrestor depth, ft
H_{max} = maximum water depth along pipeline section, ft
k = design factor for Integral Ring arrestor
L = length of buckle arrestor, in
P_a = arrestor characteristic pressure, psi
P_c = collapse pressure of the pipeline, psi
P_e = elastic buckling pressure of pipeline, psi
P_m = minimum crossover pressure, psi
P_p = propagation pressure of the pipeline, psi
P_x = crossover pressure of pipe/arrestor combination, psi
P_y = yield pressure of the pipeline, psi
P_1,P_2 = crossover pressure formulas for sleeve arrestor, psi
t = wall thickness of the pipeline, in
Y = yield strength (SMYS) of the pipeline, psi
Y_a = yield strength of the buckle arrestor, psi
γ = weight density of seawater, psi/ft
η = arrestor efficiency factor, varies between 0 and 1
λ = arrestor strength factor

Acknowledgments

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References

1. Broussard, D.E., Ayers, R.R., and Walker, G.E. Jr., Mitigation of Propagating Collapse Failures in Pipelines due to External Load, U.S.Patent 3,768,269, October 1973.
2. Langner, C.G., Arrest of Propagating Collapse Failures in Offshore Pipelines, Shell Deepwater Pipeline Feasibility Study, Report 21, January 1975.
3. Johns, T.G., Mesloh, R.E., and Sorenson, J.E., Propagating Buckle Arrestors for Offshore Pipelines, ASME J.Pressure Vessel Technology, Vol.100, pp.206-214, 1978.
4. Kyriakides, S. and Babcock, C.D., On the Slip-On Buckle Arrestor for Offshore Pipelines, ASME J. Pressure Vessel Technology, Vol.102, pp.188-193, 1980.
5. Kyriakides, S. and Babcock, C.D., Experimental Determination of the Propagation Pressure of Circular Pipes, ASME J. Pressure Vessel Technology, Vol.103, pp.32-336, 1981.
6. Kyriakides, S. and Babcock, C.D., The Spiral Arrestor: A New Buckle Arrestor Design for Offshore Pipelines, ASME J. Energy Resources Technology, Vol.104, pp.73-77, 1982. (also OTC Paper 3736, 1980.)
7. Kyriakides, S., Babcock, C.D., and Elyada, D., Initiation of Propagating Buckles from Local Pipeline Damages, ASME J. Energy Resources Technology, Vol.106, pp.79-87, 1984.
8. Yeh, M.-K. and Kyriakides, S., On the Collapse of Inelastic Thick-Walled Tubes Under External Pressure, ASME J.Energy Resources Technology, Vol.108, pp.35-47,1986.
9. Corona, E. and Kyriakides, S., On the Collapse of Inelastic Tubes Under Combined Bending and Pressure, Int'l J. Solids & Structures, Vol.24, pp.505-535, 1988.
10. Dyau, J.Y. and Kyriakides, S., On the Propagation Pressure of Long Cylindrical Shells Under External Pressure, Int'l J. Mechanical Sciences, Vol.35, pp.675-713, 1993.
11. Park, T.-D. and Kyriakides, S., On the Collapse of Dented Cylinders Under External Pressure, Int'l J. Mechanical Sciences, Vol.38, pp.557-578, 1996.
12. Power, T.L. and Kyriakides, S., Circumferential Stiffeners as Buckle Arrestors in Long Panels, Int'l J. Solids & Structures, Vol.33, pp.1837-1851, 1996.
13. Park, T.L. and Kyriakides, S., On the performance of Integral Buckle Arrestors for Offshore Pipelines, Int'l Journal of Mechanical Sciences, Vol.39, 1997.
14. Kyriakides, S., Park, T.-D., and Netto, T.A., On the Design of Integral Buckle Arrestors for Offshore Pipelines, Proc. 8th Int'l Conf on Behavior of Offshore Structures, Vol.1, pp.277-289, 1997. (Also Applied Ocean Research, Vol.20, pp.95-114, 1998.)
15. Langner, C.G., Design of Deepwater Pipelines, Proc. TNO-IWECO 30th Anniversary Symp on Underwater Technology, Netherlands, May 1984.
16. Murphey, C.E. and Langner, C.G., Ultimate Pipe Strength Under Bending, Collapse, and Fatigue, Proc. 4th Int'l Offshore Mechanics and Arctic Engineering Symp, Vol.1, pp.467-477, February 1985.

TABLE 1. FULL SCALE INTEGRAL RING BUCKLE ARRESTOR DATA

Data from Shell Integral Arrestor Tests of 12" and 18" Pipe

	PIpe Data					Arrestor Data					Observ Crosso Press	Arre Stren Fac	Arrestor Efficiency
Tes Dat	D	t(	Y(k	Pc(p	Pp(p	Da	h(	L(i	Ya(ks	Pa(p	Px	LPa/D	(Px-Pp) (Pc-Pp)
12/8	12.75	0.562	60.0	3862	802.61	15.13	1.75	2.00	53.5	10930	2130	2.136	0.434
12/8	12.75	0.562	60.0	3862	802.61	15.13	1.75	2.00	53.5	10930	2200	2.136	0.457
2/	12.75	0.562	60.0	3862	802.61	15.13	1.75	3.00	53.5	10930	3318	3.204	0.822
10/9	18.00	0.625	63.4	2340	478.36	21.25	2.25	2.50	55.3	9027	1390	2.621	0.490
10/9	18.00	0.625	63.4	2340	478.36	22.25	2.75	2.50	55.3	14611	2170	4.242	0.909

TABLE 2. SMALL SCALE INTEGRAL RING BUCKLE ARRESTOR DATA

Data from Shell Integral Arrestor Tests of 4.5" Pipe

	PIpe Data					Arrestor Data					Observ Crosso Press	Arre Stren Fac	Arrestor Efficiency
Tes Dat	D	t(	Y(k	Pc(p	Pp(p	Da	h(	L(i	Ya(ks	Pa(p	Px	LPa/D	(Px-Pp) (Pc-Pp)
1982	4.50	0.120	55.0	1151	220.24	5.16	0.33	2.00	66.0	2952	1200	5.957	1.052
1982	4.50	0.120	55.0	1151	220.24	5.16	0.33	4.00	66.0	2952	1350	11.915	1.214
1982	4.50	0.120	55.0	1151	220.24	5.16	0.33	6.00	66.0	2952	1400	17.872	1.267
1982	4.50	0.153	54.9	2130	393.85	5.16	0.33	2.00	66.0	2952	1340	3.331	0.545
1982	4.50	0.153	54.9	2130	393.85	5.16	0.33	4.00	66.0	2952	2350	6.663	1.127
1982	4.50	0.153	54.9	2130	393.85	5.16	0.33	6.00	66.0	2952	2600	9.994	1.270
1982	4.50	0.153	54.9	2130	393.85	5.36	0.43	2.00	60.0	5198	2150	5.865	1.011
1982	4.50	0.153	54.9	2130	393.85	5.36	0.43	4.00	60.0	5198	2300	11.731	1.098
1982	4.50	0.153	54.9	2130	393.85	5.36	0.43	6.00	60.0	5198	2300	17.596	1.098
1982	4.50	0.185	62.0	3409	701.62	5.16	0.33	2.00	66.0	2952	1600	1.870	0.332
1982	4.50	0.185	62.0	3409	701.62	5.16	0.33	4.00	66.0	2952	2650	3.740	0.720
1982	4.50	0.185	62.0	3409	701.62	5.16	0.33	6.00	66.0	2952	3100	5.610	0.886
1982	4.50	0.185	62.0	3409	701.62	5.36	0.43	2.00	60.0	5198	2610	3.293	0.705
1982	4.50	0.185	62.0	3409	701.62	5.36	0.43	4.00	60.0	5198	3450	6.585	1.015
1982	4.50	0.185	62.0	3409	701.62	5.36	0.43	6.00	60.0	5198	3450	9.878	1.015
1982	4.50	0.232	71.5	5714	1393.1	5.36	0.43	2.00	60.0	5198	3280	1.658	0.437
1982	4.50	0.232	71.5	5714	1393.1	5.36	0.43	4.00	60.0	5198	4440	3.317	0.705
1982	4.50	0.232	71.5	5714	1393.1	5.36	0.43	6.00	60.0	5198	5100	4.975	0.858

TABLE 3. INTEGRAL RING BUCKLE ARRESTOR DATA

Data from Kyriakides Integral Arrestor Tests of 4.5" Pipe

Tes Dat	PIpe Data D	t (	Y (k	Pc (p	Pp (p	Arrestor Data Da	h (	L (i	Ya (ks	Pa (p	Observ Crosso Press Px	Arre Stren Fac LPa/D	Arrestor Efficiency (Px-Pp) (Pc-Pp)
1995	4.52	0.209	80.9	4898	1215	4.96	0.43	2.25	68.0	5770	2693	2.365	0.401
1995	4.52	0.202	94.0	4852	1301	4.97	0.43	3.38	68.0	5770	3688	3.318	0.672
1995	4.52	0.203	91.8	4866	1287	4.97	0.428	4.50	68.0	5712	4126	4.422	0.793
1995	4.52	0.204	94.0	4958	1332	4.97	0.43	5.63	68.0	5770	4420	5.397	0.852
1995	4.52	0.204	94.0	4919	1331	4.97	0.43	6.75	68.0	5764	4632	6.468	0.920
1995	4.52	0.204	94.0	4963	1334	4.97	0.433	9.00	68.0	5873	4911	8.777	0.986
1995	4.52	0.206	80.9	4787	1175	4.80	0.35	5.63	44.8	2322	2293	2.464	0.310
1995	4.52	0.204	67.6	4295	959	4.89	0.388	5.63	44.8	2972	2726	3.864	0.530
1995	4.52	0.205	73.5	4533	1055	4.95	0.419	5.63	44.8	3574	3259	4.224	0.634
1995	4.52	0.205	73.5	4542	1055	5.09	0.489	5.63	44.8	5178	4040	6.120	0.856
1995	4.52	0.204	73.5	4482	1042	5.22	0.557	5.63	44.8	7078	4726	8.464	1.071
1995	4.52	0.204	73.5	4496	1042	5.36	0.627	5.63	44.8	9404	4853	11.245	1.103
1995	4.52	0.215	80.9	5211	1299	5.51	0.708	5.63	44.8	12567	5400	12.048	1.048
1995	4.52	0.206	84.1	4834	1220	4.83	0.359	2.25	68.0	3740	2020	1.527	0.221
1995	4.52	0.203	91.8	4852	1288	4.90	0.393	2.25	68.0	4657	2130	1.802	0.236
1995	4.52	0.203	91.8	4818	1284	4.99	0.437	2.25	68.0	5992	2834	2.322	0.439
1995	4.52	0.208	80.9	4857	1203	4.81	0.353	5.63	68.0	3597	3115	3.729	0.523

TABLE 4. GROUTED SLEEVE BUCKLE ARRESTOR DATA

Data from Shell Grouted Sleeve Arrestor Tests of 6" and 16" Pipe

Tes Dat	PIpe Data D	t (	Y (k	Pc (p	Pp (p	Arrestor Data Da	h (	L (i	Ya (ks	Pa (p	Observ Crosso Press Px	Arre Stren Fac LPa/D	Arrestor Efficiency (Px-Pp) (Pc-Pp)
2/9	6.63	0.125	50.0	431	87.1	7.13	0.25	3.00	87.0	800	250	4.156	0.474
2/9	6.63	0.125	50.0	431	87.1	7.13	0.25	5.00	87.0	800	245	6.926	0.460
2/9	6.63	0.125	50.0	431	87.1	7.13	0.25	7.00	87.0	800	258	9.696	0.497
2/9	6.63	0.190	52.4	1380	249.4	7.13	0.25	3.00	87.0	800	473	1.452	0.198
2/9	6.63	0.190	52.4	1380	249.4	7.13	0.25	5.00	87.0	800	671	2.419	0.373
2/9	6.63	0.190	52.4	1380	249.4	7.13	0.25	7.00	87.0	800	773	3.387	0.463
2/9	6.63	0.190	52.4	1380	249.4	7.39	0.38	3.00	90.0	2261	614	4.102	0.323
2/9	6.63	0.190	52.4	1380	249.4	7.39	0.38	5.00	90.0	2261	686	6.837	0.386
2/9	6.63	0.190	52.4	1380	249.4	7.39	0.38	7.00	90.0	2261	681	9.571	0.382
2/9	6.63	0.190	52.4	1380	249.4	7.60	0.48	3.00	80.0	3592	725	6.516	0.421
2/9	6.63	0.190	52.4	1380	249.4	7.59	0.48	5.00	80.0	3486	744	10.540	0.438
2/9	6.63	0.190	52.4	1380	249.4	7.58	0.48	7.00	80.0	3433	787	14.534	0.476
2/9	6.63	0.250	64.6	2863	594.1	7.58	0.48	3.00	80.0	3433	1542	2.615	0.418
2/9	6.63	0.250	64.6	2863	594.1	7.58	0.48	5.00	80.0	3451	1505	4.380	0.401
2/9	6.63	0.250	64.6	2863	594.1	7.58	0.48	7.00	80.0	3451	1437	6.133	0.371
2/9	16.00	0.378	50.9	818	152.4	[illegible]	0.75	#####	54.0	837	458	4.807	0.459
3/9	16.00	0.378	50.9	818	152.4	[illegible]	0.75	#####	54.0	837	[illegible]	3.433	0.369

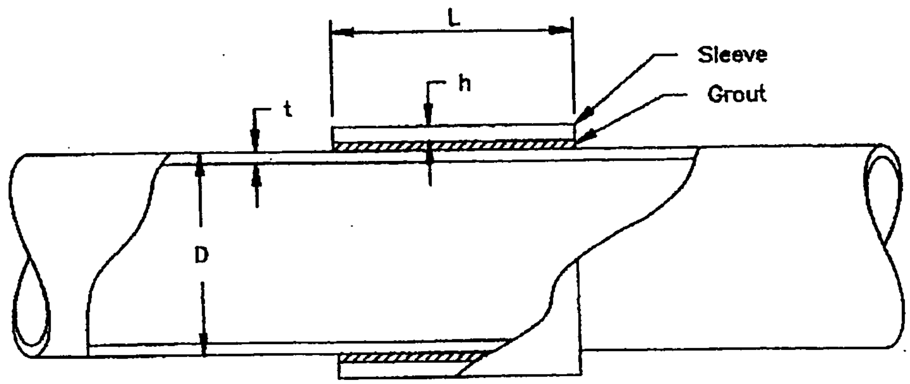

Figure 1. Grouted Sleeve Arrestor

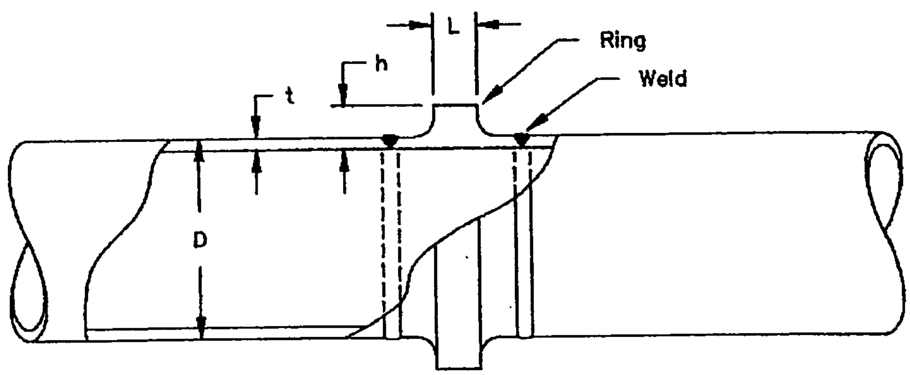

Figure 2. Integral Ring Arrestor
(Also serves as J-Lay Collar)

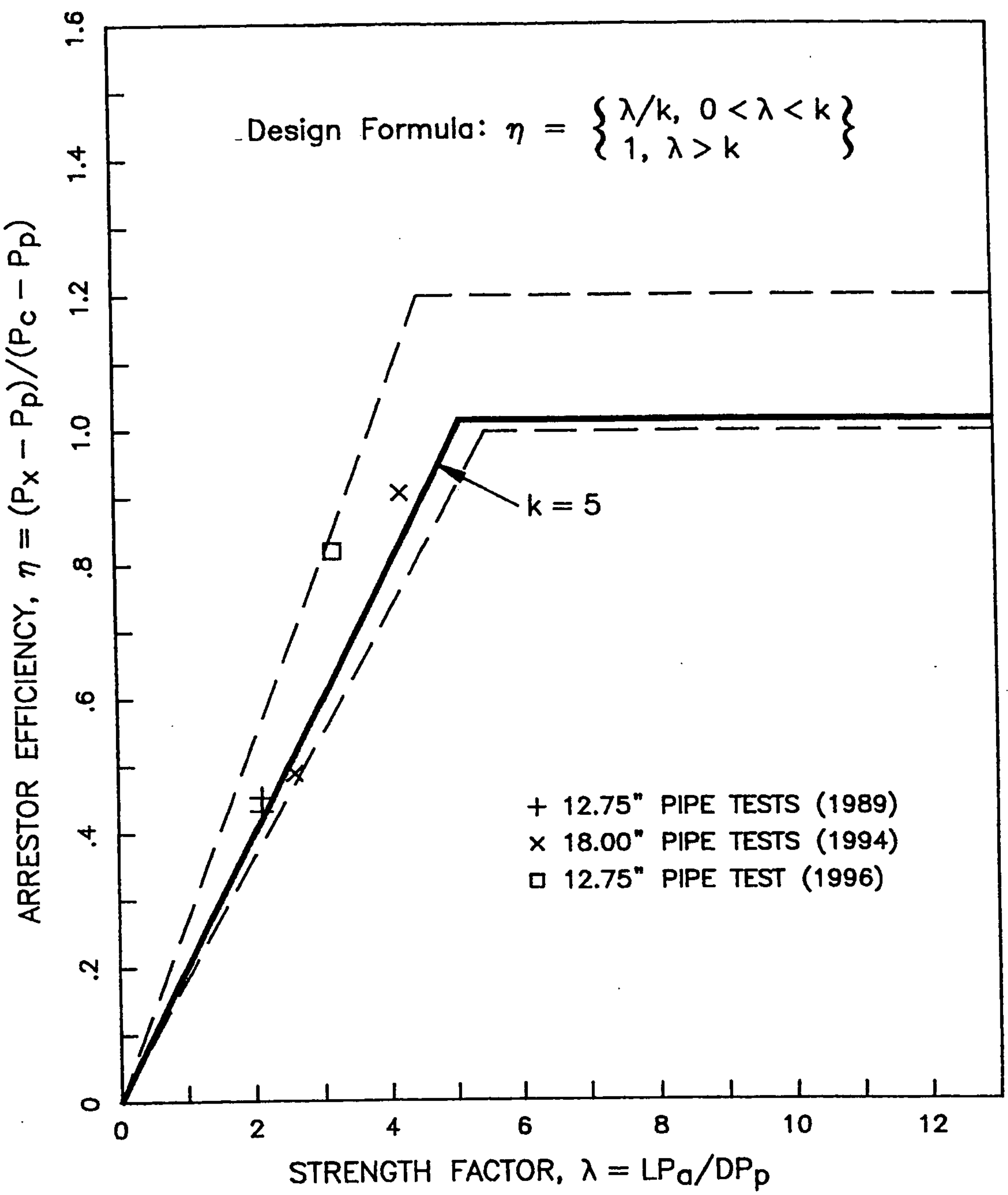

Figure 3. Comparison of Integral Ring Buckle Arrestor Design Formula with Large Scale Pipe Test Data Only

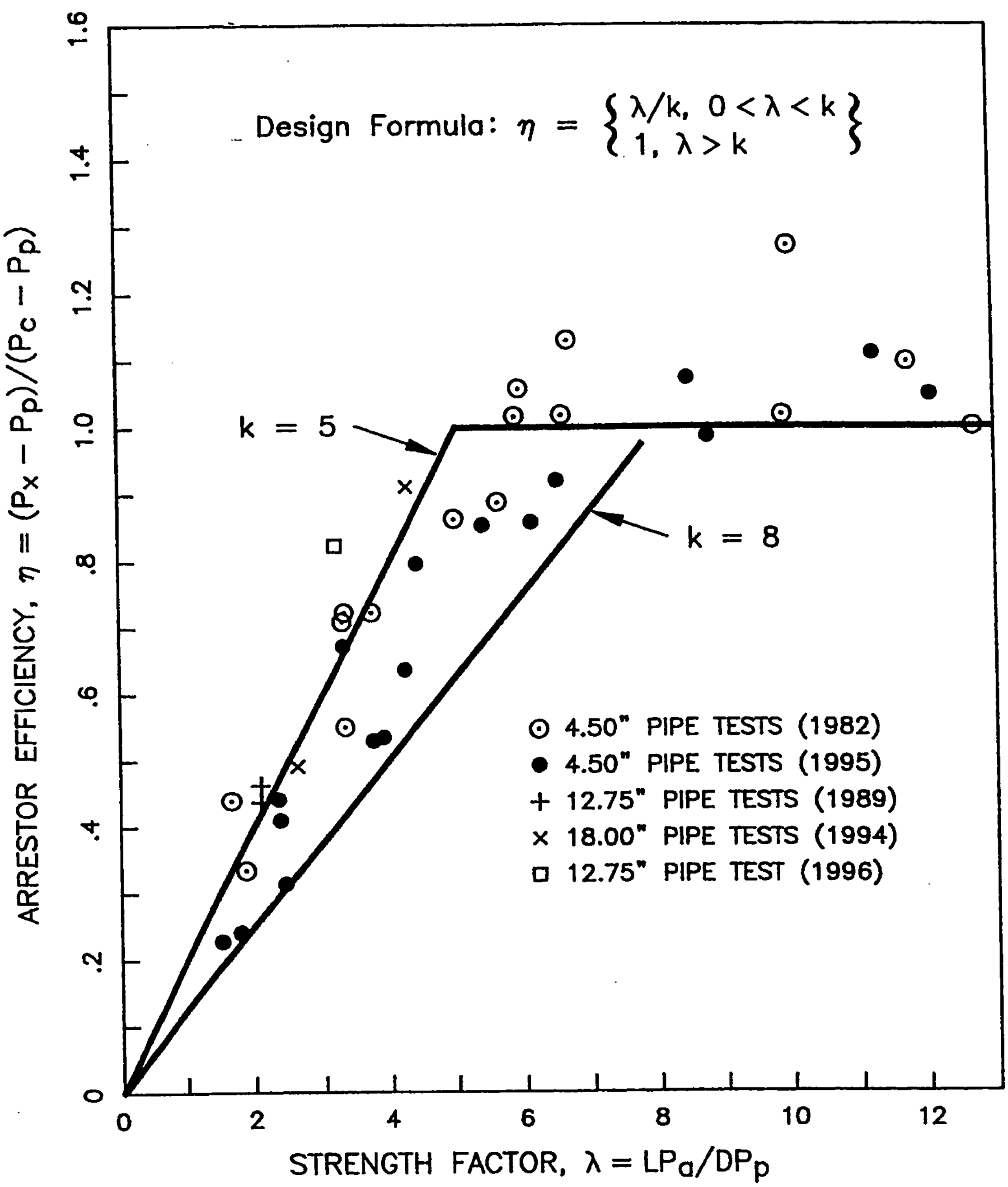

Figure 4. Comparison of Integral Ring Buckle Arrestor Design Formula with Entire Set of Available Test Data

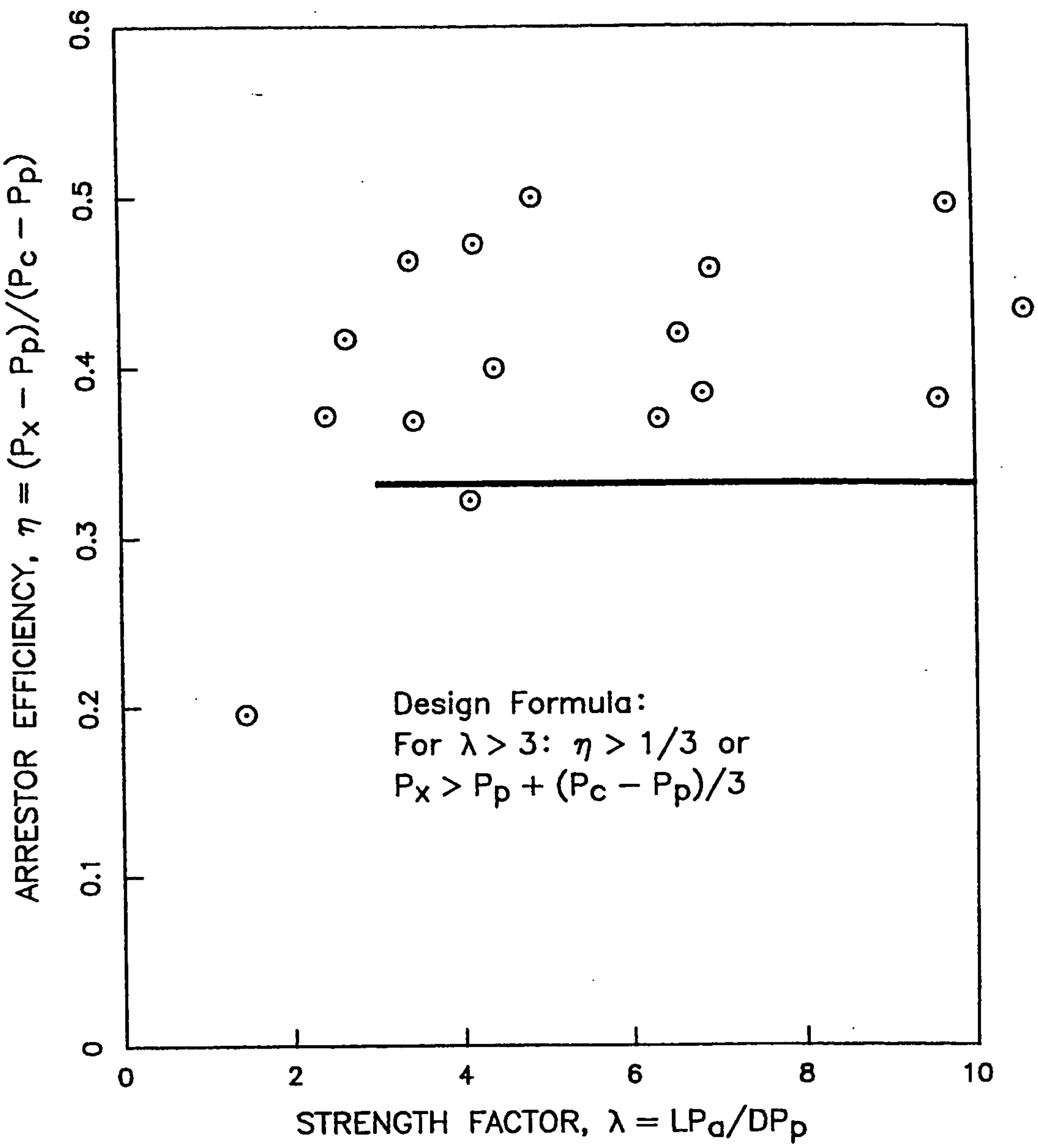

Figure 5. Comparison of Grouted Sleeve Buckle Arrestor Design Formula P2 with 1996 Test Data

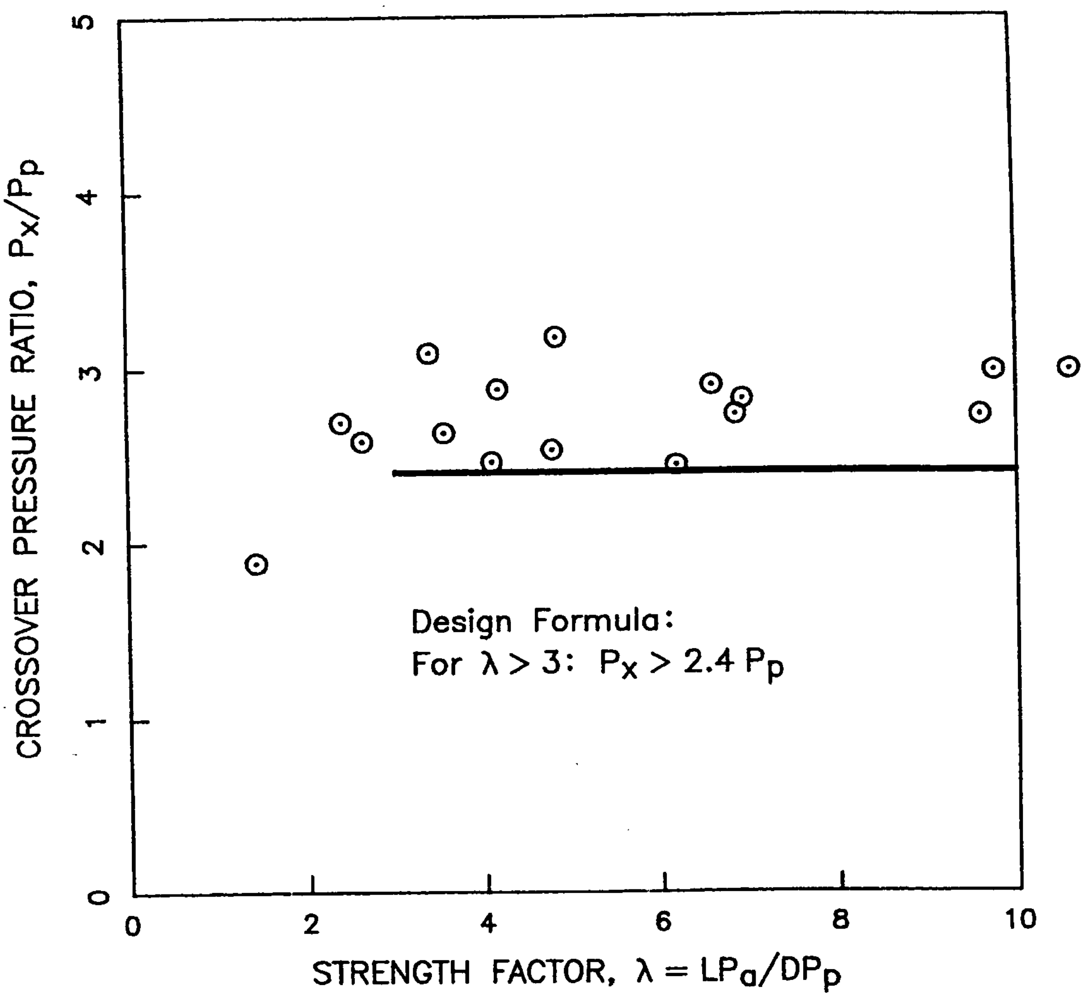

Figure 6. Comparison of Grouted Sleeve Buckle Arrestor Design Formula P1 with 1996 Test Data